



# **AN EVALUATION OF A POTENTIAL BARRIER TO THE UPSTREAM MOVEMENT OF BROOK TROUT IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO**

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# **An Evaluation of a Potential Barrier to the Upstream Movement of Brook Trout in Rocky Mountain National Park, Colorado**

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## ***EXECUTIVE SUMMARY***

Successful reclamations of stream reaches for reintroductions of native greenback cutthroat trout (*Oncorhynchus clarki stomias*) and Colorado River cutthroat trout (*O. c. pleuriticus*) largely depend on permanently excluding competing trout species, particularly brook trout (*Salvelinus fontinalis*). Such exclusion requires barriers to upstream trout movements. We conducted a field and theoretical evaluation of the barrier potential of a waterfall on the Big South Fork of the Poudre River in Rocky Mountain National Park (RMNP), CO. National Park Service (NPS) and Fish and Wildlife Service (FWS) personnel identified the waterfall as a potential fish barrier in 1998. If the waterfall could be modified to form an effective barrier, it would facilitate the reclamation of approximately 14-km of the Poudre River, 3.7 km of Chapin Creek, and Poudre Lake (5.5 ha).

To determine whether the waterfall was already a barrier, FWS personnel marked 123 brook trout in the fall of 1999. These fish were then released below the waterfall. In the fall of 2000, an electroshocking survey above the waterfall recovered six marked fish, proving that it was not a barrier to upstream movement. NPS and FWS personnel then modified the waterfall by lowering the plunge pool depth and increasing the waterfall's vertical height.

Our role in this process was to catalog the effectiveness of the modified waterfall over a 23-month interval (September 2001- August 2003). We evaluated the modified waterfall using field and theoretical approaches to determine whether it could prevent the upstream movement of brook trout. The field monitoring consisted of a mark-recapture study where we marked 626 brook trout and released them below the barrier. We then monitored a 400-m reach immediately upstream of the barrier for marked fish. Out of 1365 fish examined, three were found upstream of the waterfall.

Our theoretical evaluation of the waterfall used a laboratory-derived brook trout jumping model that was completed in April 2003. We used the pre- and post- modification waterfall dimensions in our laboratory-derived model to compare model predictions with our field results. Because of the preliminary nature of our model, the predicted probabilities of fish jumping the waterfall at the study site were extremely low. However, our model assumed that the waterfall was a sheer vertical drop, whereas the falls are more complex and appeared to include a "stair-step" arrangement. The modeling exercise was useful, nevertheless, because it identified key features of effective barriers. First, the plunge pool depth should be as shallow as possible (< 10 cm is optimal). Second, a vertical height of > 1 m effectively prevented brook trout smaller than 30 cm TL from moving upstream.

We surveyed three other potential barriers in the Hague Creek drainage. The first, on Hazeline Creek (40° 30'38" N; 105° 42'27" W), consisted of a high-gradient section that lacked any obvious vertical drop yet appeared to effectively prevent upstream fish movements. Unfortunately, the reach protected by this section is probably too short for cost-effective restoration. The second site was on Hague Creek (40° 30'37" N; 105° 40'52" W) and consisted of 1.1-m high sheer waterfall. Though this appeared to be an effective barrier, we did see one

brook trout upstream of the barrier, so minor modifications to increase the barrier function of the waterfall may be needed. One kilometer upstream from this waterfall is a definite fish barrier, formed by a 10-m high waterfall. While the habitat upstream of the barrier may be extensive enough to warrant further investigation, this upstream section is classified as “fishless” and current Park Service policy is not to stock fishless waters.

### ***ACKNOWLEDGMENTS***

The work described in this report was supported by task order 02-06 with the National Park Service. We thank J. Tilmant for his assistance in procuring funding this project; C. Kennedy, U.S. Fish and Wildlife Service, for providing background information related to jumping ability of fish and past data related to the waterfall, assistance with monthly fish and habitat sampling and making physical waterfall measurements, logistical support, guiding us to potential and functional barriers within the park, and for his comments related to our research study plan; M. Avery, M. Brandt, J. Butteris, O. Cox, G. Dethloff, T. Gump, J. Holloway, D. Holloway, J. Nicholas, M. Sullivan, E. Weber, and B. Wright for field assistance. All research described in this report followed the guidelines outlined in Animal Use Committee protocol #01-111A-01 and in the Rocky Mountain National Park permit # ROMO-2002-SCI-0068.

## Introduction

Fisheries management in the National Park system is guided by the mandate of preserving or restoring the natural behavior, genetic variability and diversity, and ecological integrity of native fish populations. In some cases, native species such as the greenback cutthroat trout (*Oncorhynchus clarki stomias*) and Colorado River cutthroat trout (*O. c. pleuriticus*) have been displaced by introduced fishes, such as the brook trout (*Salvelinus fontinalis*). The National Park Service (NPS) places a high priority on native fish restoration and they acknowledge that the removal or exclusion of non-native fishes can be the only method of guaranteeing long-term persistence of native fish populations. Rocky Mountain National Park (RMNP) in Colorado provides critical habitat for the federally threatened greenback cutthroat trout and the rare Colorado River cutthroat trout (Behnke and Zarn 1976; Young et al. 1996; Harig et al. 2000). Brook trout are also present in RMNP, and restoration efforts have targeted stream reaches that can be isolated from downstream areas.

NPS and Fish & Wildlife Service (FWS) personnel identified a waterfall on the Big South Fork of the Poudre River<sup>1</sup> as a potential fish barrier in 1998 (Figure 1). If a true barrier to upstream fish movement, the waterfall will allow the restoration of approximately 14-km of the Poudre River, 3.7 km of Chapin Creek, and Poudre Lake (5.5 ha). FWS tested the waterfall's effectiveness as a fish barrier by marking (pelvic fin clip) and displacing 123 brook trout (55-244 mm TL; mean TL  $\pm$  S.D.: 172  $\pm$  40 mm) downstream in fall 1999. The following September 6 marked fish were recaptured approximately 300 m upstream of the waterfall. This proved that the unaltered waterfall did not prevent upstream fish movement. After observing annual discharge patterns, NPS and FWS personnel modified the waterfall by decreasing the plunge pool depth and raising the vertical height of the falls in October 2001.

After the waterfall modifications, it was important to monitor the system to determine if it proved impassable to fish. Our (Colorado State University) role in this process was to monitor the site for 23 months, sampling monthly from June-October each year. We also recorded the post-modification physical dimensions of the waterfall for use in our simulation model. Because we were concurrently developing a laboratory-based model of brook trout jumping performance, we hoped to use the results from the field study to help check the accuracy of our model. The specific objectives of our research project are listed below.

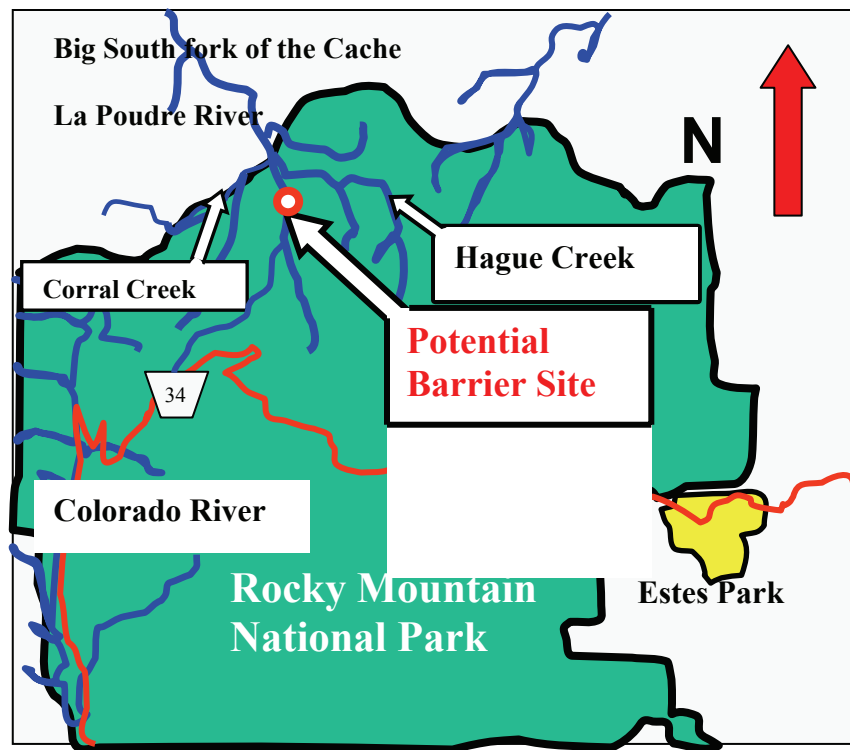
## Research Objectives

1. Quantify the physical changes made to a large waterfall on the Big South Fork of the Poudre River and determine if the modified waterfall was impassable to brook trout following modification.
2. Determine if the laboratory-derived brook trout jumping performance model was valid in field situations by running the model using fish movement data and waterfall dimension data from the Big South Fork of the Poudre River.

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<sup>1</sup> This site is located roughly 3.0 km south of the junction of La Poudre Pass Creek with the Big South Fork of the Poudre River (N 40° 31'23"; W 105°44'48").

3. Evaluate other potential barriers to the upstream movement of brook trout in Rocky Mountain National Park.
4. Develop guidelines for fish barrier selection and construction in the National Park System.



**Figure 1.** Location of the potential fish barrier on the Cache La Poudre River in Rocky Mountain National Park, CO.

## **Methods and Materials**

### **Description of Study Area**

Our study site was concentrated around the waterfall (N 40° 30.772', W 105°44.225'), located approximately 3.0 km upstream of the junction of La Poudre Pass Creek with the Big South Fork of the Cache la Poudre River (Figure 1). The site included the plunge pool, located directly below the waterfall and extending approximately 50 m downstream, and the segment of the river extending approximately 500 m upstream of the waterfall. Our survey work involved searching for other potential fish barriers within the RMNP Cache La Poudre drainage.

### **Waterfall Measurements**

We obtained physical measurements of the waterfall and river under study and developed contour plots of the waterfall and its associated pools before and after modification. This information was then used to make theoretical predictions of the ability of brook trout to pass this barrier based on a brook trout jumping performance model being developed through concurrent laboratory studies. The detailed measurements were limited to the waterfall and the area immediately below and above the waterfall. The contour plots were developed by measuring water depth (cm) at 50-cm intervals along transects that were spaced 50-cm apart. These transects were set perpendicular to the flow of the river. Because of the danger involved with taking measurements during peak (i.e., runoff) flows, we only made detailed measurements of the waterfall during low-flow periods. The data from these transects was entered into a Microsoft Excel spreadsheet; the contour plots were generated in DeltaGraph 5.0.

### **Brook Trout Displacement Study**

The purpose of the displacement study was to determine if brook trout were able to move upstream past the modified waterfall. Sampling was conducted once per month from June – September 2002) and twice (July and August) in 2003. Brook trout were collected from the 435-m reach above the waterfall using a Smith-Root Model 12B backpack electrofisher. The 435-m reach was divided into 4 segments roughly 100 m in length. Table 1 provides coordinates and the length of stream sampled for each of these segments.

We used two-pass depletion sampling in each segment and held all brook trout in live cars until they were processed. All fish were lightly anesthetized in water containing 25 mg/L MS-222 buffered with 0.5 g/L NaHCO<sub>3</sub> and 3 mg/L NaCl and examined for any previous marks or tags. Measurements of standard length (SL, in mm), fork length (FL, in mm), and total length (TL, in mm) were made and the fish was weighed to the nearest 0.1 g on a portable electronic balance. The first 100 unmarked fish over 100 mm TL were batch marked with an adipose fin clip and tagged with a Northwest Marine Technology visual implant alphanumeric tag (VI-alpha tag)<sup>2</sup> before being transferred to a recovery bath until they regained their equilibrium. Fish less than 100 mm TL were marked with an adipose fin clip and held for release below the waterfall. The marked and tagged fish were released below the waterfall. The purpose of displacing a large

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2 Northwest Marine Technology, P. O. Box 427, Ben Nevis Loop Road, Shaw Island, WA 98286, USA

number of the fish was to increase our recapture probability, should the waterfall still be passable to fish. Fish captured after the 100-fish quota had been reached were not marked or displaced downstream but were weighed, measured, checked for previous marks (VI-alpha tags and clipped fins) before release at the capture site.

**Table 1:** Locations and lengths of stream segments sampled upstream of the waterfall site on Big South Fork of the Cache La Poudre River, RMNP, CO.

Segment	Latitude/Longitude Start	Latitude/Longitude End	Total distance (m)
1	N 40° 30.767' W 105° 44.210'	N 40° 30.706' W 105° 44.221'	128.5 m
2	N 40° 30.706' W 105° 44.221'	N 40° 30.676' W 105° 44.274'	90 m
3	N 40° 30.676' W 105° 44.274'	N 40° 30.620' W 105° 44.263'	109 m
4	N 40° 30.620' W 105° 44.263'	N 40° 30.550' W 105° 44.281'	107 m

### **Field validation of brook trout jumping model**

The second objective of this study was to compare the field results (fish movement past the waterfall) with the predicted results from a preliminary model of brook trout jumping performance we generated in a concurrent laboratory study. The model (shown below) was developed with data collected from the jumping performance of 11,000 hatchery-reared fish in three size categories (100-150 mm, 150-200 mm, and >200 mm TL). Jumping performance data were collected using adjustable waterfalls with variable waterfall heights ( $h_1$ ) and plunge pool depths ( $h_2$ ). We tested pool depths of 10 to 60 cm and waterfall heights of 10 to 90 cm. Throughout the study, we maintained constant temperature ( $11 \pm 1^\circ\text{C}$ ), flows (570 L/min), experimental duration (24-hr), and fish batch size (25 fish per run).

$$\text{Logit}(P) = 4.81 - 0.17(h_1) - 0.03(h_2) + 0.089(TL) - 0.0017(\text{time}) - 0.48(\text{cond}) + 0.0017(h_1 \times h_2) - 0.0016(h_2 \times TL) - 1.12(EBV)$$

The model predicts that the probability of a fish jumping over a waterfall is a function of waterfall height ( $h_1$ ; cm), plunge pool depth ( $h_2$ ; cm), experiment duration ( $\text{time}$ ; minutes), fish condition ( $\text{cond}$ ), fish total length ( $TL$ ; cm), and two complex interaction terms ( $h_1 \times h_2$  and  $h_2 \times TL$ ). A random component (based on replicated experimental trials) was used to check for evidence of extra-binomial variation ( $EBV$ ) in our data and to adjust confidence intervals for the beta estimates accordingly.

To compare the model's predictions with our field results, we entered the waterfall height of the site of interest and used the following assumptions: 1) the waterfall is a vertical drop; 2) the fish are in good physical condition; 3) the plunge pool is  $\leq 60$  cm deep, and; 4) the fish have at least 24 hours to try to jump over the waterfall. We ran simulations for the following sites: main falls (pre- and post-modification), side-channel falls (pre- and post-modification) and the Hague Creek fish barrier, according to the physical dimensions of each waterfall. We also ran simulations using the sizes of the 3 brook trout that were recaptured above the waterfall to determine the predicted probability of their success.

### **Evaluation of other potential barriers**

The final research objective was to work with NPS and FWS personnel to identify and evaluate other potential barriers in Rocky Mountain National Park. FWS personnel provided us with the locations of these potential barriers (all in the Hague Creek drainage). We evaluated these potential barriers by: 1) taking measurements of their waterfall height; 2) visually inspecting them; 3) running their dimensions through our preliminary model of brook trout jumping performance, and; 4) conducting a visual search with FWS personnel for fish above the potential barrier.

## **Results and Discussion**

### **Waterfall Measurements**

Detailed measurements of the stream and waterfall were made on two dates. We measured the waterfall on October 12, 2001 before modifications were completed and also on September 28, 2002 after waterfall modifications. Flows were lower in 2002 than in 2001 ( $0.1 \text{ m}^3/\text{s}$  compared to  $0.06 \text{ m}^3/\text{s}$ ). Modifications to the waterfall were made before we had completed our laboratory-based brook trout jumping evaluations and therefore were based on the combined experience of National Park Service and US Fish and Wildlife Service personnel. The goal of the modification was to make the waterfall impassable to fish by increasing the height while decreasing the plunge pool depth, particularly along the side chute. Specifically, boulders were removed from the tail of the plunge pools to further decrease pool depths and effectively increase vertical waterfall height, the pools above the waterfalls were filled in with rock material to restrict water movement and create a potential water velocity barrier in the landing area, and rocks were dropped into the plunge pools to further decrease the plunge pool depths, create more aerated water conditions below the falls, and increase the downstream distance of the standing wave from the base of the falls to make conditions less optimal for jumping fish (Figure 2).

Measurements made in both 2001 and 2002 included the vertical distance of drop on the main channel and an adjacent side channel, the lower plunge pool depth and shape on both the main channel (limited by higher flows in 2001) and side channel falls, and the upper pool depth and shape (at the head of the side channel falls). A comparison of the results of the contour maps

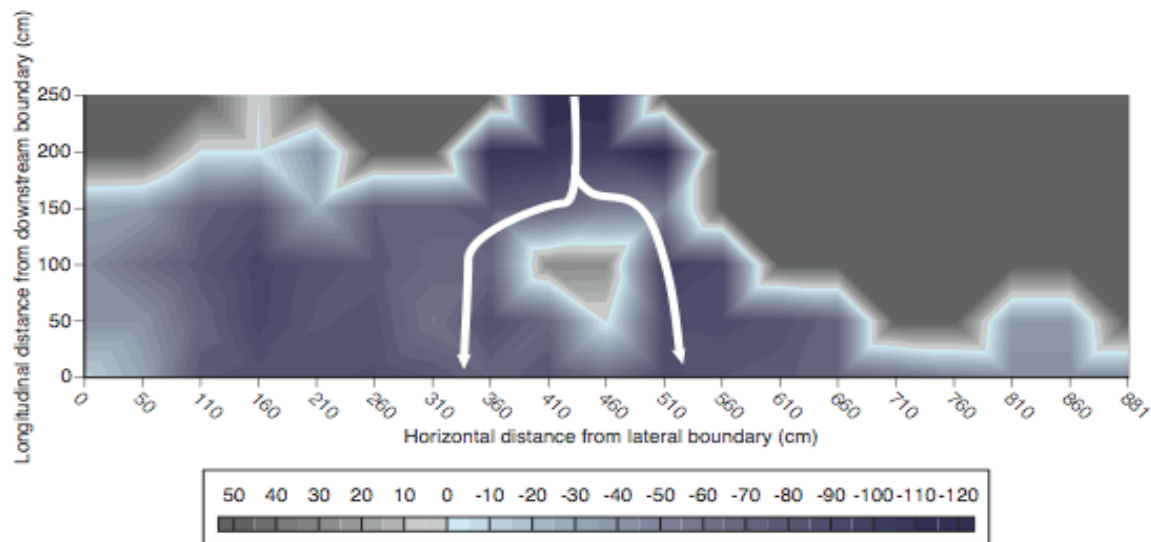
developed from these measurements before and after the waterfall modifications were made is discussed below.



**Figure 2.** Physical appearance of side-chute channel drop (a.) and main-fall channel drop (b.) before modification and main-fall channel drop (c.) and side-chute channel drop (d.) after modification of a natural waterfall on the Big South Fork of the Poudre River, RMNP, CO. Dimensions for “before” were measured on October 12, 2001 when the flow was approximately  $0.10 \text{ m}^3/\text{s}$  (3.7 cfs). Dimensions for “after” were measured on September 28, 2002 when flow was approximately  $0.06 \text{ m}^3/\text{s}$  (2.1 cfs).

### ***Main Falls***

The maximum depth of the plunge pool on the main falls was decreased from 1.50-m to 1.00-m (measured in front of the splash zone of the falls) after modifications<sup>3</sup>. The depth at the tail of the post-modified plunge pool was 0.17-m, giving a residual depth of 0.83 m. Prior to modifications, we were unable to make more detailed measurements of the rest of the main fall plunge pool because depths were too great. However, we measured the post-modified plunge pool in more detail in order to develop a contour map (Figure 3). The minimum distance from the pool surface to the waterfall crest was measured as 2.0-m before modifications and was measured as 1.9-m after modifications. The lower vertical height measured in 2002 was probably a result of the lower flows during this year, which decreased the height of the crest of the main falls.



**Figure 3.** Contour map of the plunge pool located downstream of the main-falls after modification. Dimensions were measured on September 28, 2002 when the flow was 0.058 m<sup>3</sup>/s (2.1 cfs). Arrows indicate flow direction. The color scale indicates water depth (cm) from the surface (0 cm) to the deepest point of the pool (-50 cm).

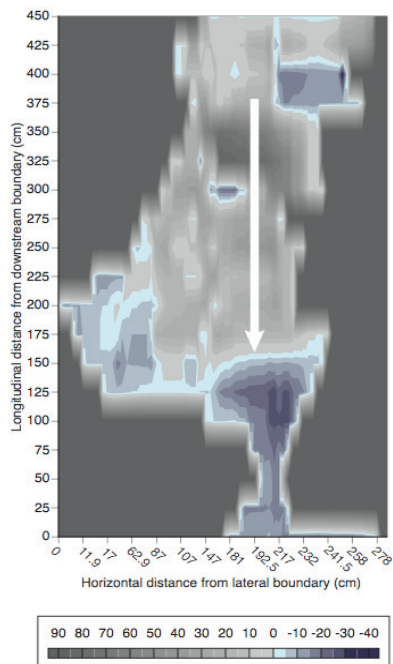
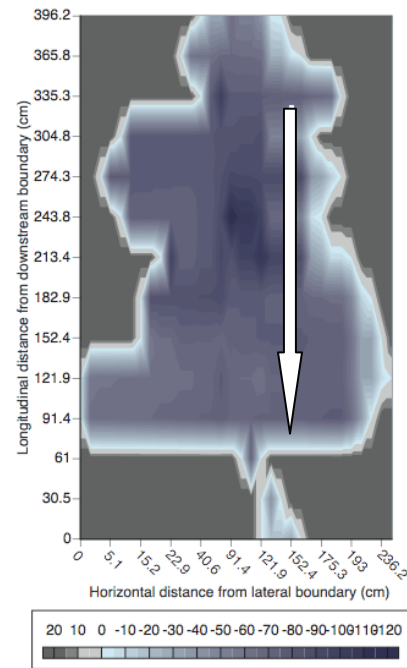
### ***Side-Channel Falls***

After modifications, the maximum plunge pool depth of the side-channel falls decreased from 1.17-m to 0.36-m and the portion of the pool under 0.10 m in depth increased greatly (see Figures 4 and 5). The minimum distance from the pool surface to the waterfall crest increased from 1.17-m to 1.38-m and the deepest portion of the upper pool was reduced from approximately 1.1-m 0.3-m (see Figures 6 and 7).

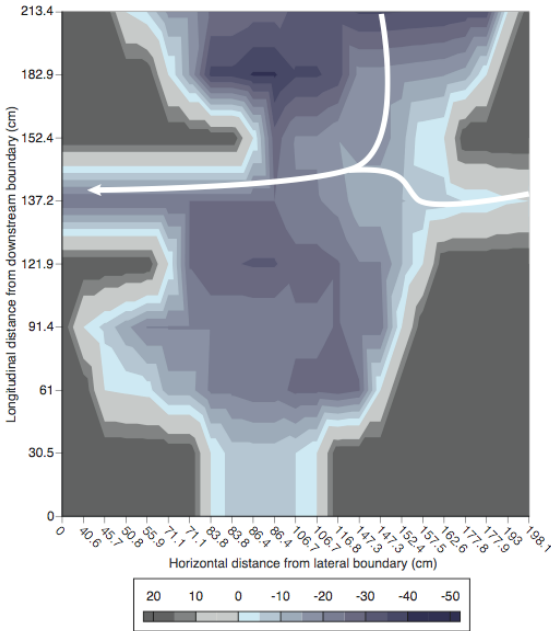
<sup>3</sup> A maximum depth of 1.20 m occurred behind the splash zone of the waterfall after modification. However, a fish in this position would not likely be able make take off attempts.

**Figure 4.** Contour map of the plunge pool located downstream of the side-channel portion of the barrier **before modification**.

Dimensions were measured on October 12, 2001 when the flow was  $0.1 \text{ m}^3/\text{s}$  (3.7 cfs). Arrow indicates flow direction. The color scale indicates water depth (cm) from the surface (0 cm) to the deepest point of the pool (-50 cm).

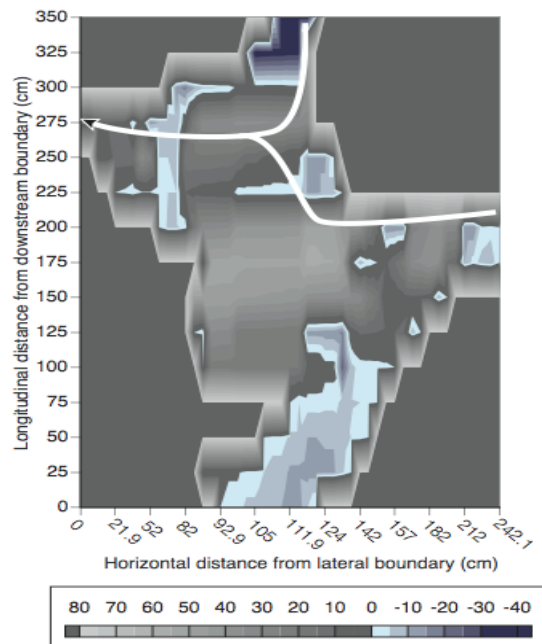


**Figure 5.** Contour map of the plunge pool located downstream of the side-channel portion of the barrier **after modification**. Dimensions were measured on September 28, 2002 when the flow was  $0.058 \text{ m}^3/\text{s}$  (2.1 cfs). Arrow indicates flow direction. The color scale indicates water depth (cm) from the surface (0 cm) to the deepest point of the pool (-50 cm).



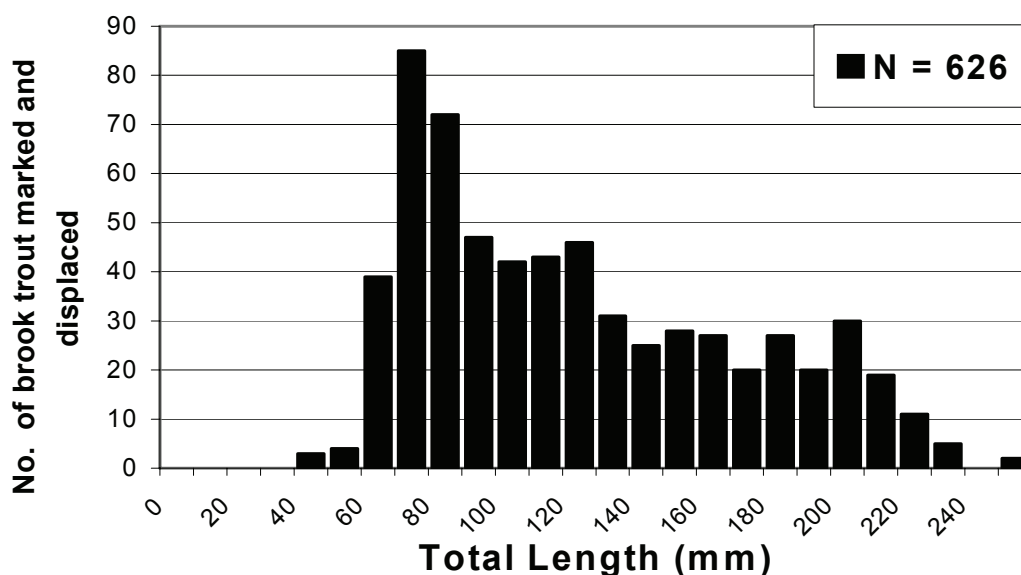
**Figure 6.** Contour map of the upper pool located upstream of the side-channel portion of the barrier **before modification**. Dimensions were measured on October 12, 2001 when the flow was  $0.1 \text{ m}^3/\text{s}$  (3.7 cfs). Arrows indicate direction of flow. The color scale indicates water depth (cm) from the surface (0 cm) to the deepest point of the pool (-50 cm).

**Figure 7.** Contour map of the upper pool located upstream of the side-channel portion of the barrier **after modification**. Dimensions were measured on September 28, 2002 when the flow was  $0.058 \text{ m}^3/\text{s}$  (2.1 cfs). Arrows indicate direction of flow. The color scale indicates water depth (cm) from the surface (0 cm) to the deepest point of the pool (-50 cm).



## **Fish Movement and Monitoring**

We captured and examined 1,240 brook trout upstream of the waterfall during the 2002 sampling trips. Of these fish, no marked individuals were detected upstream of the waterfall after waterfall modifications were completed in October 2001. Eighty-one brook trout were marked and relocated below the waterfall in October 2001 and an additional 545 brook trout were similarly marked and relocated during the period from June 2002 through September 2002 (Figure 8). None of these marked fish were recaptured above the waterfall during the 2002 surveys. We did however recapture seven fish that had been marked in 1999.



**Figure 8.** Size distribution of 626 brook trout marked and displaced below the waterfall from 2001 and 2002. None of these fish were recaptured above the waterfall during our 2002 surveys, but 3 fish (TL: 96, 166, and 177 mm) were recaptured during surveys in 2003.

In 2003, we made two trips to the study site during July and August (Table 2). The region experienced above-normal snowfall and spring run-off in 2003 in contrast to the below-normal water conditions present in 2002. This allowed us to observe if the change in hydraulics would allow brook trout to pass over the waterfall. No new fish were marked or relocated during these sampling trips, but all captured fish were examined for previous marks, weighed, and measured. Six hundred seventy brook trout were captured and examined in July and August 2003. Of these fish, three individuals (0.48%) had been previously marked with an adipose clip but none had retained a VI alpha tag.

Our 2002 sampling trips suggested that brook trout were not capable of moving past the modified waterfall, but in 2003 we did recapture 3 marked brook trout above the waterfall. One fish (TL: 166 mm; weight: 42 g) was captured in segment 4, between 328 and 435 m upstream of the waterfall during July 2003. Two additional fish were captured in August 2003. One of these

(TL: 96 mm; weight: 9.1g) was captured in segment 2 (129 – 219 m upstream); the other (TL: 177 mm, weight: 51.5 g) was captured in segment 4. Although these fish represent only 0.5% of the 626 fish that were marked and relocated below the waterfall, they indicate that some fish are capable of negotiating the modified falls. We re-inspected the waterfall after finding fish upstream and noted that while the main falls still appeared impassable, the side-chute might, under certain conditions, create “stair-step” falls that brook trout could use to move upstream.

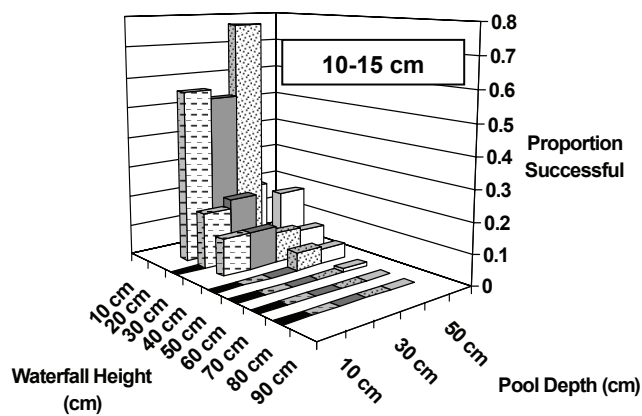
**Table 2:** Disposition of brook trout captured on sampling trips conducted on the Big South Fork of the Cache La Poudre River, RMNP, CO. Trips made before October 12, 2001 were before the barrier was modified. No marked fish were recaptured in 2002, but 3 fish were recaptured in 2003.

Date	Brook trout captured during sampling			Recaptures of fish marked in 1999		Recaptures of fish marked in 2001 or 2002	
	N	Mean ( $\pm$ SE) TL (mm)	Mean ( $\pm$ SE) weight (g)	N	TL (mm)	Number	TL
9/15/99	123	172.0 $\pm$ 3.6	61.0 $\pm$ 3.3	–	–	–	–
9/19/00	166	150.5 $\pm$ 3.5	43.3 $\pm$ 2.6	6	160; 161; 178; 178; 189; 213	–	–
10/19/01	81	163.1 $\pm$ 5.0	48.0 $\pm$ 3.0	4	171; 192; 200; 245	–	–
6/15 – 6/16/02	122	117.6 $\pm$ 4.2	19.8 $\pm$ 1.9	1	206	0	–
7/13 – 7/18/02	359	134.3 $\pm$ 2.4	31.8 $\pm$ 1.5	2	167; 184	0	–
8/17 – 8/19/02	445	114.7 $\pm$ 2.4	23.8 $\pm$ 1.2	0	–	0	–
9/14 – 9/15/02	314	109.1 $\pm$ 2.6	19.4 $\pm$ 1.4	0	–	0	–
9/28 – 9/29/02	–	–	–	–	–	–	–
7/26 – 7/27/03	337	130.0 $\pm$ 2.0	26.0 $\pm$ 1.1	0	–	1	166
8/15 – 8/16/03	333	132.7 $\pm$ 2.1	27.9 $\pm$ 1.2	0	–	2	96; 177
<b>Total or Mean</b>	2280	129.5 $\pm$ 1.0	29.4 $\pm$ 0.6	13	188	3	146

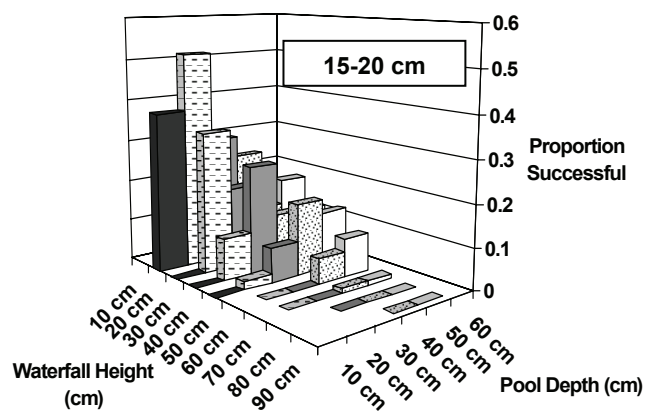
No fish longer than 20 cm TL were recaptured above the falls. Finding *smaller* fish upstream is contradictory to the findings from our laboratory tests of brook trout jumping behavior (Figures 9a-9c) and model predictions (Figure 10). These results showed that the larger fish (20+ cm TL) should have had the greatest probability of jumping over the waterfalls, as fish  $\leq$  15 cm TL only jumped a maximum height of 63.5 cm and fish  $\geq$  15 cm jumped a maximum height of 73.5 cm under laboratory conditions. Some degradation of jumping and swimming performance is expected under laboratory conditions, particularly when hatchery-reared fish are used (Duthie 1987), but it is unlikely that this is the principal reason for the gross disparity between the laboratory and field results. One explanation is that it is unlikely the recaptured fish ascended the falls by jumping from plunge pools over the falls in one jump. The fish that were found upstream may have been small enough to use intermediate pools located in the face of the falls (particularly prevalent on the side-chute) to ascend the falls in smaller steps. Other possible

explanations are that the fish were intentionally moved above the falls by anglers or that were capable of using interstitial spaces in the side-channel area to move upstream. The side channel area is comprised of boulders packed tightly together and not bedrock. If fish were able to move past the side-channel falls by swimming through small interstitial spaces upstream, this might explain why only smaller fish were found upstream of the falls in 2002. Perhaps additional flow in 2003 provided conditions necessary for fish passage through interstices while lower flows in 2002 blocked use of these interstitial spaces for upstream movement.

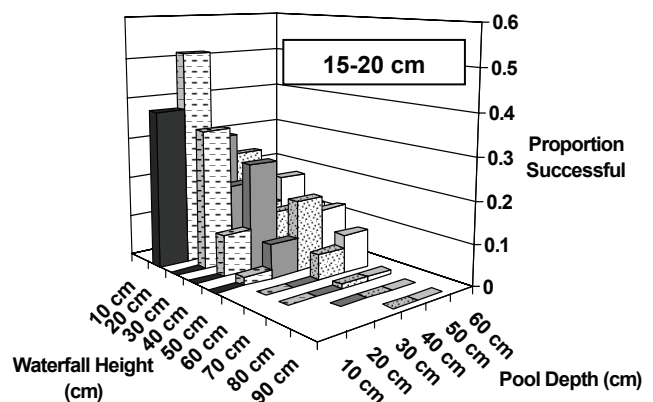
A.



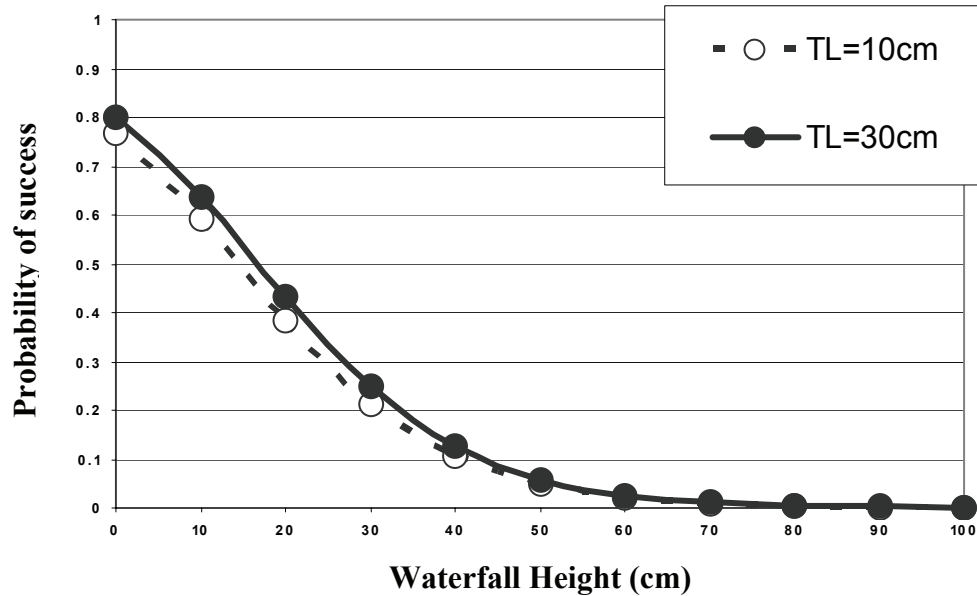
B.



C.



**Figure 9 (A, B, C).** Results of laboratory tests of Brook trout jumping over a waterfall of fixed height. Proportion successful (Z-axis); height (Y-axis, cm) and fixed pool depth (X-axis, cm) for fish in the 10-15 cm TL (Figure 9a), 15-20 cm TL (Figure 9b), and 20+ cm TL (Figure 9c) size classes. Blank spaces represent height  $\times$  depth combinations for which no data were collected.



**Figure 10.** Model results using the best AIC<sub>c</sub> model for a healthy, 10 cm and 30 cm total length brook trout jumping over a waterfall for a fixed pool depth of 60 cm (maximum depth tested).

### Evaluation of Other Potential Barriers

We surveyed three potential barriers in the vicinity of our primary study site on the Poudre River. All sites were in the Hague Creek drainage, which is a tributary of the Big South Fork of the Poudre River.

The first site was located on a nameless tributary (hereafter referred to as “Hazeline Creek”) flowing out of Hazeline Lake (40° 29’36” N; 105° 42’10” W, elevation roughly 3400 m) that enters Hague Creek (flowing south to north) at the upper end of the lowest big meadow (40° 30’38” N; 105° 42’27” W) in the Hague Creek drainage. The gradient of Hazeline Creek decreases as it approaches Hague Creek. FWS personnel noted brook trout (along with a few cutthroat trout) throughout the lower portion of the stream. They found that brook trout numbers decreased with increasing distance from the confluence with Hague Creek, while cutthroat trout numbers increased with increasing distance from the confluence. Also, they identified a distinct point along this stream where brook trout were no longer present and cutthroat trout continued to persist. This point was not distinguished by barriers that obviously segregated cutthroat populations from brook trout, however the stream became increasingly higher in gradient with many complex log and boulder drop structures. There may be unidentified factors (other than waterfalls) restricting upstream brook trout movement that would be worthy of investigation. However, the small amount of stream habitat the barrier site creates (up to Hazeline Lake) may not justify further restoration efforts.

The next potential barrier was located along the uppermost portion of Hague Creek, less than 300 m below timberline (40° 30.220' N; 105° 40.874' W). The waterfall is located directly downstream from a small meadow in a bedrock-constrained segment of the stream. The stream cuts through a 200-m long canyon section with steep (approximately 20 m high) walls. The flow directly upstream of the site (40° 30.202' N; 105° 40.863' W) was 0.07 m<sup>3</sup>/s on September 29, 2002. The elevation (measured by a Garmin GPS) at the site was 3159 m. The waterfall had a main falls where most of the water was flowing, and a side-channel falls where a smaller amount of water was flowing. The minimum vertical distance from the surface of the plunge pool to the crest of the main falls was 1.1 m; the minimum vertical distance of the side chute falls was 1.3 m (Figure 11). The plunge pool beneath the waterfall had a maximum depth of 0.8-m, was 6.1-m long, and 4.1-m wide, but the water depth directly below the waterfall was only 0.4 m. The depth of the pool beneath the side channel falls was 0.6 m. The pool above the falls had a maximum depth of 0.53 m.

**Figure 11.** Waterfall on Hague Creek, a tributary of the Big South Fork of the Poudre River, RMNP, CO. Dimensions were measured on September 29, 2002 at flows of 0.07 m<sup>3</sup>/s (2.4 cfs). The main falls (shown) are 1.1 m in height. The splash from the side-channel falls can be seen in the background (right).



FWS personnel observed brook trout and very few cutthroat trout downstream of this barrier. Until our September 2002 trip, there appeared to be only cutthroat trout upstream of this barrier but one brook trout was noted in a beaver pond located just above the potential barrier. The presence of the lone brook trout above the waterfall could serve as justification for making minor modifications to the waterfall to prevent further upstream movements. However, like the

Hazeline Creek site, the small amount of stream (about 1 km) protected by this potential barrier may be too small to warrant further restoration attempts.

Upstream of this barrier, Hague Creek meanders through a sub-alpine meadow with evidence of beaver activity, including at least one fairly large pond (where the lone brook trout was observed). The meadow is approximately 1 km long and is bounded upstream by a 10-m tall waterfall that should be a barrier to any upstream movement of fish. We observed cutthroat trout throughout the stream up to the plunge pool at the base of the upstream falls. The tall waterfall upstream of the waterfall was only visually inspected and was not measured in detail, since it clearly was impassable to fish (10 m vertical drop). The waters upstream of the large waterfall bounding the upper end of Hague Creek meadow do not currently support fish populations. Historically, these streams were stocked with fish, but no fish populations remain (Chris Kennedy, personal communication). Earlier fish plants may have failed due to poor stocking procedures (stocking eggs instead of fry) or possibly because of unfavorable thermal regimes.

### **Theoretical Waterfall Evaluation**

The laboratory-derived model of brook trout jumping success predicted that fish would have very low probabilities of jumping over the waterfall, given the dimensions we entered into the model. However, the results from our fish monitoring study clearly demonstrate that some fish were able to get over the waterfall, thus showing that our model is not a good predictor of brook trout jumping performance under field conditions. The reasons for the lack of concordance between the model prediction and our field results are as follows:

The model was developed using data on the jumping performance of hatchery reared brook trout that were tested under a fixed set of conditions (waterfall height, plunge pool depth, flow, etc.) *that did not include* the waterfall heights or plunge pool depths observed in the field study. The apparatus used to measure jumping performance was constrained by the facility to a maximum pool depth of 60 cm and a maximum waterfall height of 93.5 cm. This seemingly disheartening result does have some benefits, which are discussed below.

The laboratory study and subsequent modeling exercise identified several factors that help determine the ability of fish to jump over waterfalls. The most important of these are waterfall height, plunge pool depth, fish size, and fish condition. From a management standpoint, little can be done to regulate fish size or condition, but managers can alter waterfall heights or plunge pool depths. Based on these results, measurements of waterfall height and plunge pool depth should be taken throughout the year so that they cover the full range of hydrologic conditions at the site. Our project was not intended to carry out such measurements, which would require a much more logistically and technically intensive sampling effort. Because we do not have year-round information on the waterfall, our model predictions are based on a single snapshot of flow conditions and do not track well with our field results.

Although the model predictions do not track well with the field data, the modeling results are valuable because they help identify the relative vulnerability of the two areas of the Poudre River

barrier (main falls vs. side chute). The probabilities of successful upstream passage generated for fish of the same length as those recaptured upstream (Table 3) indicate that the barrier potential of the side-channel falls was improved by the NPS modifications. However, observations made in summer 2003 suggest that the plunge pool has been scoured out and deepened considerably since measurements were made during fall 2002. Based on these observations, we feel that the side-channel continues to be the most vulnerable location for fish upstream fish passage.

**Table 3:** Probability of success computed for 3 brook trout that successfully jumped over waterfall during 2003 on the Big South Fork of the Poudre River. The following are abbreviations:  $H_1$  = vertical waterfall height,  $H_2$  = plunge pool depth, and TL = total length. Fish total lengths were used to compare probabilities of success for pre-modification conditions on the Big South Fork of the Poudre River as well as for the Hague Creek barrier.

Waterfall site	Probability of success		
	TL = 9.6 cm	TL = 16.6 cm	TL = 17.7 cm
Main falls: pre-modification $H_1 = 200$ cm, $H_2 = 60$ cm	0.00036%	0.00035%	0.00035%
Main falls: post-modification $H_1 = 190$ cm, $H_2 = 60$ cm	0.00071 %	0.00068 %	0.00067 %
Side-channel falls: pre-modification $H_1 = 97$ cm, $H_2 = 60$ cm	0.34 %	0.33 %	0.32 %
Side-channel falls: post-modification $H_1 = 138$ cm, $H_2 = 36$ cm	0.00022 %	0.00028 %	0.00029 %
Hague Creek falls $H_1 = 90$ cm, $H_2 = 60$ cm	0.54 %	0.52 %	0.52 %

Our observations of the waterfall and the low probabilities generated by the model suggest that it is unlikely that brook trout are capable of negotiating the falls with a single jump. This statement is also supported by the findings of other researchers. It seems more likely that the fish found upstream jumped over the waterfall in smaller stages or swam upstream through interstitial spaces. Reiser and Peacock (1985) used a simple formula for computing the maximum height fish can jump according based on rectilinear motion for uniform acceleration:  $HL = v^2/2g$ , where  $HL$  is the leap height of the fish,  $v$  is the initial burst speed of the fish, and  $g$  is gravitational acceleration. Their formula assumed a pool depth of no less than 2.5 m. Based on this formula, they computed the maximum height attainable for “adult” brown trout and cutthroat trout as 76.2 cm and 85.3 cm from a still pool. Using a more conservative approach modified from Aaserude and Orsborn (1985), the upward force produced by a standing wave (48.7 cm/s) and the total length of the fish are included in the formula:  $HL = v_T^2/g + L$ , where  $HL$  is the leap height of the fish,  $v_T$  is the burst speed of the fish plus the force produced by the standing wave, and  $L$  is the total length of the fish. This formula predicts that a 9.6 cm TL brook trout (size of fish recaptured above the falls) with a darting speed of 387 cm/s and standing wave force of 48.7 cm/s could jump 106 cm. The minimum distance fish must jump to clear the Poudre River waterfall is 138 cm over the side-channel falls from a 0.36-m deep plunge pool. This distance is

greater than the maximum predicted heights measured in our model, by Reiser and Peacock's (1985) formula, and Aaserude and Osborn's formula.

## **Management Recommendations**

### **Poudre River Study Site**

The main Poudre River waterfall appears to be an impassable barrier to brook trout in its current configuration, but the side-channel fall warrants further attention. We recommend that further modifications be made to the Poudre River waterfall in order to make this site an effective fish barrier. The lower side-channel plunge pool should be made shallower by the addition of larger rocks that will not be displaced by high flows, thereby increasing the difficulty of effective fish passage. It appeared that the pool beneath this waterfall had either been scoured out by high spring flows or artificially deepened by park visitors. If possible (in terms of logistics and personnel safety), the falls should be observed during spring runoff to determine if a series of "stair-step" falls develop. We suspected this may be the mechanism behind the successful upstream passage of some fish, but verifying the presence of stair-step falls was beyond our capabilities. As with the first set of modifications completed by the NPS, we would recommend post-modification monitoring for at least 2 years to check for movement of fish past the waterfall.

### **Barrier Selection Guidelines**

The maximum height jumped by brook trout in our laboratory study was 73.5 cm. This is probably not the absolute maximum height that brook trout in the 20 – 30 cm range can jump, so we are hesitant to use it as the minimum height for an effective barrier. We did find that shallow plunge pools severely reduced jumping ability, with brook trout only being able to jump a maximum height of 33.5 cm from a 10-cm deep pool. Therefore, until a more comprehensive study of brook trout jumping performance is completed, we make the following recommendations for barrier selection and design:

1. Plunge pools should be as shallow as possible, preferably < 10 cm deep, and should maintain this reduced depth over a range of flows.
2. The vertical drop should be at least 1 m high, particularly if larger brook trout are present in the system. It is important to note that this 1 m height should exist even under high flow conditions.
3. The vertical drop or face of the waterfall should be truly vertical, or even undercut. If a stair-step arrangement is present, then each "stair riser" should be treated as an individual waterfall and evaluated accordingly.
4. Sites should be observed under varying flow conditions to determine where lowest vertical drops occur and to measure flow-related changes in vertical height and plunge pool depth. This will probably require an understanding of the most favorable conditions for fish passage (most likely under high flow conditions, with lowest vertical height and deepest plunge pool depths).

## Literature Cited

- Aaserude, R. G., and J. F. Orsborn. 1985. Final Project Report: New concepts in fish ladder design. Washington State University, Department of Civil and Environmental Engineering.
- Behnke, R. J. and M. Zarn. 1976. Biology and management of threatened and endangered western trout. U.S. Forest Service, Fort Collins, Colorado.
- Clancy, C. G. and D. R. Reismuth. 1990. A detachable fishway for steep culverts. North American Journal of Fisheries Management 10:244-246.
- Duthie, G. G. 1987. Observations of poor swimming performance among hatchery-reared rainbow trout, *Salmo gairdneri*. Environmental Biology of Fishes 18:309 - 311.
- Harig, A. L., K. D. Fausch, and M. K. Young. 2000. Factors influencing success of greenback cutthroat trout translocations. North American Journal of Fisheries Management 20:994-1004.
- Kennedy, C., U.S.F.W.S, personal communication.
- Reiser, D. W. and R. T. Peacock. 1985. A technique for assessing upstream fish passage problems at small-scale hydropower developments. Pages 423-432 in F.W. Olson, R. G. White, and R. H. Hamre, editors. Symposium on small hydropower and fisheries. American Fisheries Society, Western Division, Bethesda, Maryland.
- Young, M. K., R. N. Schmal, T. W. Kohley and V. G. Leonard. 1996. Conservation and status of Colorado River cutthroat trout *Oncorhynchus clarki pleuriticus*. U.S. Forest Service, Fort Collins, Colorado.



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